Thermal Conductivity and Durability Testing of Materials for Inflatable Buildings

for:
NSF, Office of Polar Programs, Arctic Research Support and Logistics Program

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BACKGROUND

The NSF ARC-RSL Program is interested in utilizing new technologies to increase the variety of building structures available for use in the field. Inflatable structures offer the potential to provide a rapidly deployable, logistically efficient (lower weight, ease of setup, smaller cargo space required, etc.), cost-effective shelter for use in cold climates. The addition of insulating layers, in addition to the air space, could also make the structures more energy-efficient than traditional tent structures or conventionally-constructed buildings. Recent communications and site visits to 3rd party vendors (e.g. ILC Dover) and other government facilities (Natick Test Center) led to the idea of conducting thermal conductivity and durability tests on fabrics and insulating materials currently used in inflatable building concepts. This report presents the results obtained from the tests.

MATERIALS AND TEST PROCEDURES

CRREL received samples of four potential materials that could be used as inflatable skins, and two potential insulating materials. Additionally, a search of local fabric stores added two additional insulating options to the mix. The building skin materials were:

Building Skin Material	Thickness (inches/layer) as tested	Unit Cost (sq. yd)
Tan Polyurethane Double-Sided Coated Nylon	0.027	$20.70
Blue Polyurethane Single-Sided Coated Nylon	0.0095	$5.86
White Polyurethane Single-Sided Coated Nylon	0.0095	$5.86
Blue Drop Thread Fabric	0.1260	$46.00

The potential insulating materials were:

Insulating Material	Thickness (inches/layer) as tested	Unit Cost (sq. yd)
Thinsulate G200 with 3M Backing	0.25	$3.14
Thinsulate G200 without Backing	0.375	$3.14
Polyester/Cotton Blend (20%/80%)	0.066	$3.40
100% Polyester	0.375	$5.00

Each of the materials was tested in our LaserComp thermal conductivity measurement instrument to determine its thermal conductivity, and calculate the corresponding R-value (Figure 1). We also constructed and tested “sandwich panels” of one layer of building skin and one to multiple layers of insulation to obtain the thermal conductivity and calculate the R-values of potential wall sections. The test instrument consists of flat plates that are set to prescribed temperatures on each side with a 12” X 12” sample of test material sandwiched in the middle. The time it takes for the temperature to equilibrate from one side to the other is then used to determine the test material’s thermal conductivity.

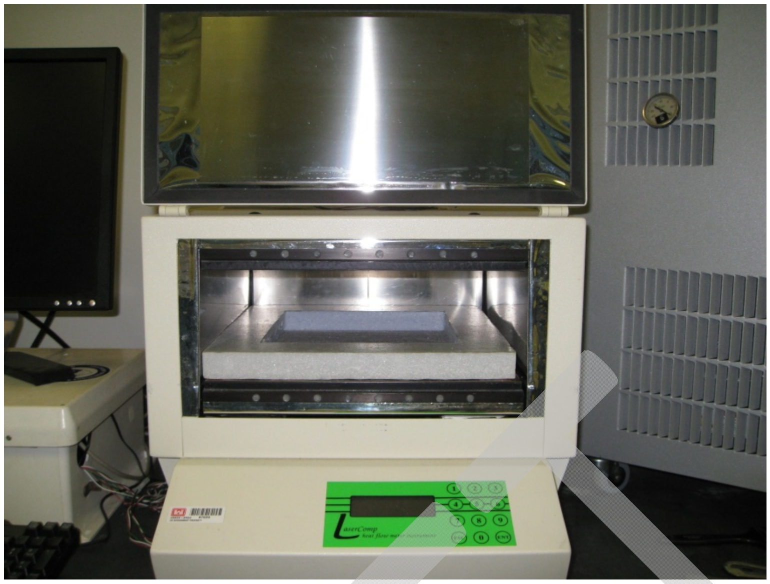


Figure 1: LaserComp thermal conductivity test instrument.

The durability tests were conducted in CRREL's -40C cold box. Six-inch by six-inch samples of each of the eight materials were "cold soaked" for approximately 6-hours laying flat at -40C. The samples were individually flexed and creased for 10-cycles to determine if any cracking would occur during bending from a flat shape to a doubled-over shape (Figure 2). A second set of durability tests was conducted with each of the samples initially folded-over in half then placed back in the cold box with a weight on them to keep them folded as they were cold soaked to -40C again, overnight. Each sample was unfolded slowly to determine whether it cracked on the initial bend, and was subsequently creased over 10-cycles (as before) to see if repeated bending would cause any cracking.

Figure 2: Sample undergoing cycling in -40 cold box.

RESULTS

Thermal Conductivity

The results of the thermal conductivity tests on 12 different sandwich panel configurations are presented in Appendix A: Chart 1 and Table 1. All samples displayed virtually a linear increase in R-Value (reporting units: (˚F ft^2 hr)/Btu) with thickness. The thickness of each sandwich panel sample, as tested, is presented in Appendix A: Table 2. The linear trend was expected when increasing the wall section thickness with the same material. Thus the results appeared accurate and were also repeatable. The highest measured R-value (5.29) was obtained with the blue or white polyurethane single-sided coated nylon with 3-layers of unbacked Thinsulate G200. The lowest R-value (1.05) was obtained with the drop thread material and one layer of 3M backed Thinsulate G200.

Along with the significant variability in R-values (4.13) over the range of these configurations, there were also significant cost differences. The estimated cost for a square yard of each sandwich panel configuration is presented in Appendix A: Table 3. The sample that yielded the highest R-value (blue or white polyurethane single-sided coated nylon with three layers of unbacked Thinsulate G200) cost approximately $15.28/sq. yd. In general, the polyurethane single-sided coated nylon panels were the cheapest at approximately $9 to $66 per square yard, the polyurethane double sided coated nylon panels were mid-range cost at approximately $24 to $81 per square yard, and the drop thread panels were by far the most expensive at $49 to $106 per square yard. The range of costs associated with each shell material was due to the number of layers of insulating material contained in each sample wall section. A quick look at the cost of insulation alone indicates the Thinsulate G200 (same cost and R-value backed or unbacked) is the best value at approximately $3.14 per square yard.

Durability

The first set of durability tests were conducted after cold-soaking the samples for 6-hours. All samples except the drop thread fabric performed adequately after being cold-soaked at -40C and flexed for 10 cycles from laying flat. The polyurethane samples demonstrated very minor increases in stiffness, and all of the insulation samples behaved as they did at normal room temperatures. The drop thread material was very stiff, produced audible cracking, and ultimately delaminated during this test (Figure 3).

Figure 3: Delamination of drop thread fabric after bending.

We obtained similar results when the materials were cold-soaked overnight in the flexed orientation and unfolded and cycled 10 additional times. The drop thread sample displayed “bubbling” due to further delamination, and the internal fibers appeared to either separate or rip as well (Figures 4 and 5). In addition, the polyester/cotton insulation sample collected moisture. It is unclear if that was a result of the cotton or because it was the last sample taken from the cold box so had been repeatedly exposed to the higher humidity of the test room. Notes from the durability are included in Appendix A: Table 5.

Figure 4: “Bubbling” of drop thread fabric caused by delamination.

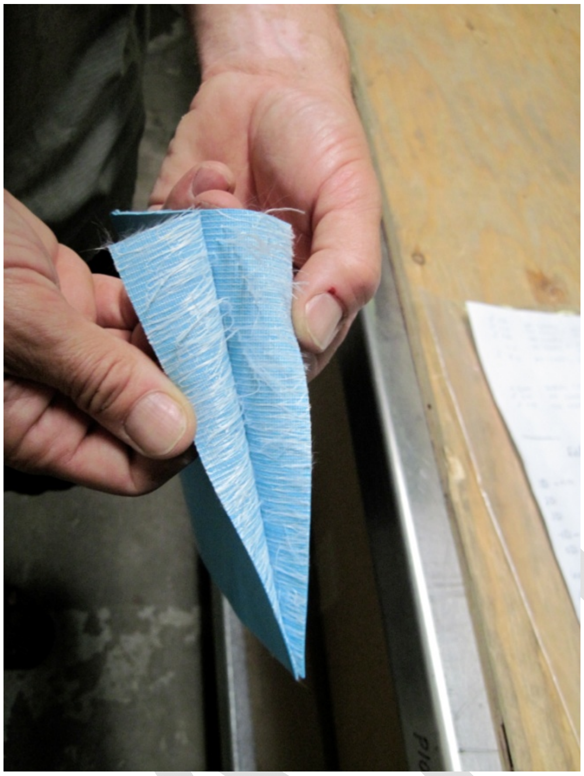
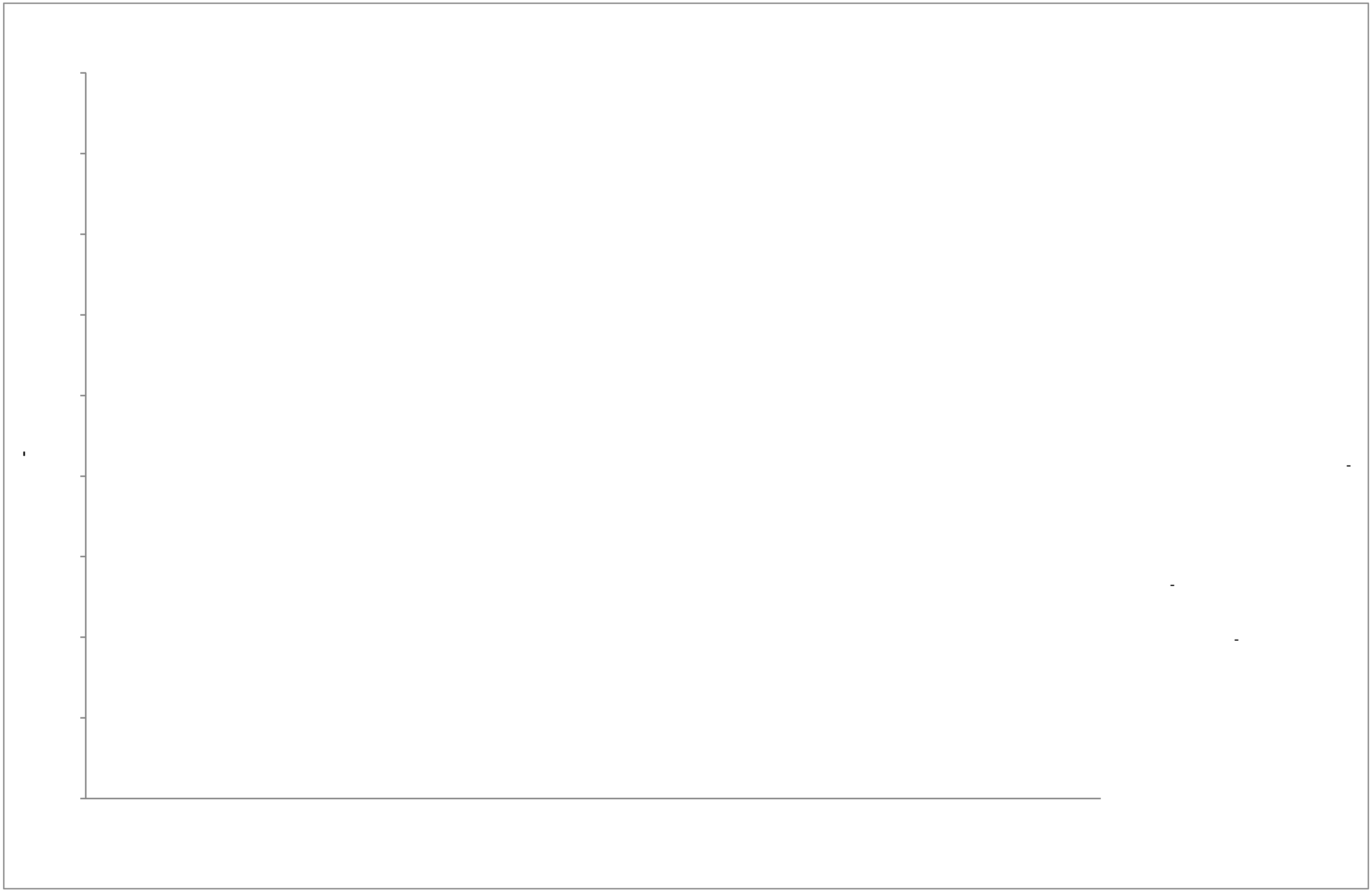


Photo 5: Ripping and/or separation of drop thread fibers.

CONCLUSIONS AND RECOMMENDATIONS

CRREL conducted a series of thermal conductivity and durability tests on potential materials for constructing inflatable building wall-sections. The results of the R-value tests indicated that the blue or white polyurethane single-sided coated nylon building skin with three layers of unbacked Thinsulate G200 insulation yielded the highest R-value of 5.29. Those materials also remained flexible at -40C and survived repeated bending/folding with only very minor stiffening and no indication of cracking or material damage. Though it wasn't the cheapest wall section tested, at roughly $15/sq. yd, at approximately $3/sq. yd/R, it was the most efficient combination when the costs were normalized by R-value (reference Appendix A: Table 4). Two factors of particular importance during development of this concept are: 1) be sure that both the wall shell material and the insulating material remain flexible at cold temperatures, and 2) the insulating material must remain hydrophobic at all times – that is more important than achieving a slightly higher R-value when comparing competing materials. Based on the R-value obtained, the durability and the unit cost/R, CRREL recommends further pursuit of the polyurethane single-sided coated nylon (or similar product) with a single layer of Thinsulate (or similar insulation) as a prototype wall section for inflatable structures in Polar Regions.

APPENDIX A



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APPENDIX A

Table 1: R-Value Test Results for Insulated, Inflatable Building Materials

Number of Insulating Layers	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate w/3M Backing	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate without Backing	Tan Polyurethane Double-Sided Coated Nylon w/100% Polyester	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	Blue Polyurethane Single-Sided Coated Nylon w/100% Polyester
1	1.153	1.7505		1.224	***1.824***	
2	2.333	3.489		2.4255	***3.562***	
3	3.49	5.242		3.565	***5.2878***	
4			1.7			***1.766***
8			3.4			***3.466***
12			5.104			***5.176***

Number of Insulating Layers	White Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	White Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	White Polyurethane Single-Sided Coated Nylon w/100% Polyester	Blue Drop Thread w/ Thinsulate w/3M Backing	Blue Drop Thread w/Thinsulate without Backing	Blue Drop Thread w/100% Polyester
1	1.226	1.818		1.047	1.664	
2	2.399	**		2.226	3.423	
3	**	**		3.394	5.157	
4			1.766			1.61
8			**			3.315
12			**			5.0185

* Highlighted values in this table are averages of original tests and repeated tests. The tests were accurate and repeatable.
**Tests not repeated because of similar results with both blue and white polyurethanes - they have essentially the same R-Value.
Values in ***Bold Italics*** were the highest measured R-Values for given number of layers.

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Table 2: Thickness of Each Wall Section as Tested

Number of Insulating Layers	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate w/3M Backing	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate without Backing	Tan Polyurethane Double-Sided Coated Nylon w/100% Polyester	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	Blue Polyurethane Single-Sided Coated Nylon w/100% Polyester
1	0.250	0.375		0.250	0.375	
2	0.500	0.750		0.500	0.750	
3	0.750	1.125		0.750	1.125	
4			0.375			0.375
8			0.750			0.750
12			1.125			1.125

Number of Insulating Layers	White Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	White Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing - single point only	White Polyurethane Single-Sided Coated Nylon w/100% Polyester - single point only	Blue Drop Thread w/ Thinsulate w/3M Backing	Blue Drop Thread w/Thinsulate without Backing	Blue Drop Thread w/100% Polyester
1	0.250	0.375		0.250	0.375	
2	0.500	**		0.500	0.750	
3	**	**		0.750	1.125	
4			0.375			0.375
8			**			0.750
12			**			1.125

**Tests not repeated because of similar results with both blue and white polyurethanes - they are the same thickness.

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Table 3: Estimated Cost Per Unit (square yard) for Insulated, Inflatable Building Materials

Number of Insulating Layers	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate w/3M Backing	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate without Backing	Tan Polyurethane Double-Sided Coated Nylon w/100% Polyester	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	Blue Polyurethane Single-Sided Coated Nylon w/100% Polyester
1	$23.84	$23.84		$9.00	$9.00	
2	$26.98	$26.98		$12.14	$12.14	
3	$30.12	$30.12		$15.28	$15.28	
4			$40.70			$25.86
8			$60.70			$45.86
12			$80.70			$65.86

Number of Insulating Layers	White Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	White Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	White Polyurethane Single-Sided Coated Nylon w/100% Polyester	Blue Drop Thread w/ Thinsulate w/3M Backing	Blue Drop Thread w/Thinsulate without Backing	Blue Drop Thread w/100% Polyester
1	$9.00	$9.00		$49.14	$49.14	
2	$12.14	**		$52.28	$52.28	
3	**	**		$55.42	$55.42	
4			$25.86			$66.00
8			**			$86.00
12			**			$106.00

**Tests not repeated because of similar results with both blue and white polyurethanes - they have the same cost as blue poly.

APPENDIX A

Table 4: Estimated Cost Per Unit, Normalized by R-Value ($/sq. yd/R)

Number of Insulating Layers	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate w/3M Backing	Tan Polyurethane Double-Sided Coated Nylon w/Thinsulate without Backing	Tan Polyurethane Double-Sided Coated Nylon w/100% Polyester	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	Blue Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	Blue Polyurethane Single-Sided Coated Nylon w/100% Polyester
1	$20.68	$13.62		$7.35	$4.93	
2	$11.56	$7.73		$5.01	$3.41	
3	$8.63	$5.75		$4.29	$2.89	
4			$23.94			$14.64
8			$17.85			$13.23
12			$15.81			$12.72

Number of Insulating Layers	White Polyurethane Single-Sided Coated Nylon w/Thinsulate w/3M Backing	White Polyurethane Single-Sided Coated Nylon w/Thinsulate without Backing	White Polyurethane Single-Sided Coated Nylon w/100% Polyester	Blue Drop Thread w/ Thinsulate w/3M Backing	Blue Drop Thread w/Thinsulate without Backing	Blue Drop Thread w/100% Polyester
1	$7.34	$4.95		$46.93	$29.53	
2	$5.06	**		$23.49	$15.27	
3	**	**		$16.33	$10.75	
4			$14.64			$40.99
8			**			$25.94
12			**			$21.12

**Tests not repeated because of similar results with both blue and white polyurethanes - they have the same unit cost as blue poly.

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Table 5: Cold/Durability Testing at -40C

Test Case #1: Cold Soak Flat and Cycle with 10 Bends

Sample #	Sample Description	Comments On Bend Cycling
1D	Tan Polyurethane Double-Sided Coated Nylon	No cracking, very little increase in stiffness
2D	Blue Polyurethane Single-Sided Coated Nylon	No cracking, very little increase in stiffness
3D	White Polyurethane Single-Sided Coated Nylon	No cracking, very little increase in stiffness
4D	Thinsulate with 3M Backing	No cracking, no increase in stiffness
5D	Thinsulate without Backing	No cracking, no increase in stiffness
6D	Blue Drop Thread	Audible cracking, very stiff, delaminated
6aD	20%Polyester with 80%Cotton	No cracking, no increase in stiffness
7D	100% Polyester	No cracking, no increase in stiffness

Test Case #2: Cold Soak Doubled Over and Cycle with 10 Bends

Sample #	Sample Description	Comments On Bend Cycling
1D	Tan Polyurethane Double-Sided Coated Nylon	No cracking, was stiff after cold soak
2D	Blue Polyurethane Single-Sided Coated Nylon	No effect
3D	White Polyurethane Single-Sided Coated Nylon	No effect
4D	Thinsulate with 3M Backing	No cracking, stuck together (perhaps due to high humidity)
5D	Thinsulate without Backing	No cracking, stuck together (perhaps due to high humidity)
6D	Blue Drop Thread	Loud cracking, delamination, ripples, fibers appear to be separating/ripping
6aD	20%Polyester with 80%Cotton	No change, collected some moisture (perhaps due to high humidity)
7D	100% Polyester	No change